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NATIONAL STANDARD
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REFERENCE DATA SYSTEM

Physical Properties Data Compilations Relevant to Energy Storage.

V. Mechanical Properties Data on Alloys for Use in Flywheels

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No. 61
PART V
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Physical Properties Data Compilations Relevant to Energy Storage.

V. Mechanical Properties Data on Alloys for Use in Flywheels

NSRDS-NBS 61, Part V

H. M. Ledbetter

Fracture and Deformation Division
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NATIONAL STANDARD
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Foreword

The National Standard Reference Data System provides access to the quantitative data of physical science, critically evaluated and compiled for convenience and readily accessible through a variety of distribution channels. The System was established in 1963 by action of the President's Office of Science and Technology and the Federal Council for Science and Technology, and responsibility to administer it was assigned to the National Bureau of Standards.

NSRDS receives advice and planning assistance from a Review Committee of the National Research Council of the National Academy of Sciences-National Academy of Engineering. A number of Advisory Panels, each concerned with a single technical area, meet regularly to examine major portions of the program, assign relative priorities, and identify specific key problems in need of further attention. For selected specific topics, the Advisory Panels sponsor subpanels which make detailed studies of users' needs, the present state of knowledge, and existing data resources as a basis for recommending one or more data compilation activities. This assembly of advisory services contributes greatly to the guidance of NSRDS activities.

The System now includes a complex of data centers and other activities in academic institutions and other laboratories. Components of the NSRDS produce compilations of critically evaluated data, reviews of the state of quantitative knowledge in specialized areas, and computations of useful functions derived from standard reference data. The centers and projects also establish criteria for evaluation and compilation of data and recommend improvements in experimental techniques. They are normally associated with research in the relevant field.

The technical scope of NSRDS is indicated by the categories of projects active or being planned: nuclear properties, atomic and molecular properties, solid state properties, thermodynamic and transport properties, chemical kinetics, and colloid and surface properties.

Reliable data on the properties of matter and materials are a major foundation of scientific and technical progress. Such important activities as basic scientific research, industrial quality control, development of new materials for building and other technologies, measuring and correcting environmental pollution depend on quality reference data. In NSRDS, the Bureau's responsibility to support American science, industry, and commerce is vitally fulfilled.

E. Ambler.

Ernest Ambler, *Director*

Preface

This series of publications is aimed at providing physical properties data on materials used in energy storage systems. It was inspired by a requirement in the Department of Energy's Division of Energy Storage Systems for materials property data needed by its contractors in the timely development of energy storage devices. As prime contractor for this program, the Lawrence Livermore Laboratory (LLL) has requested the Office of Standard Reference Data (OSRD) to manage the task of gathering the data, using its established network of data centers and other identified sources of expertise. The OSRD monitors the progress of work, reviews the results, and conveys the numerical data to LLL where the data are converted for entry into an automated data storage and retrieval system. Every effort is made to supply data which have been critically examined in light of the latest knowledge concerning theory and experiment. However it must be recognized that in a rapidly moving technology some of the data will be superseded rather quickly as new materials and techniques are introduced. Thus access to the data via computer terminal as well as publication in this series should help provide the practitioner with timely and useful data which he requires to solve his problems in energy storage. Funding for this series of projects from the Department of Energy, Division of Energy Storage, through the Lawrence Livermore Laboratory, is gratefully acknowledged.

Previous publications in the series "Physical Properties Data Compilations Relevant to Energy Storage":

Janz, George J., Allen, Carolyn B., Downey, Joseph R., Jr., and Tomkins, R. P. T., Physical Properties Data Compilations Relevant to Energy Storage. I. Molten Salts Eutectic Data, Nat. Stand. Ref. Data Ser., Nat. Bur. Stand. (U.S.), 61, Part I, 244 pp. (March 1978).

Janz, G. J., Allen, C. B., Bansal, N. P., Murphy, R. M., and Tomkins, R. P. T., Physical Properties Data Compilations Relevant to Energy Storage. II. Molten Salts: Data on Single and Multi-Component Salt Systems, Nat. Stand. Ref. Data Ser., Nat. Bur. Stand. (U.S.), 61, Part II, 442 pp. (Apr. 1979).

Miller, G. R., and Paquette, D. G., Physical Properties Data Compilations Relevant to Energy Storage. III. Engineering Properties of Single and Polycrystalline Sodium Beta and Beta" - Alumina, Nat. Stand. Ref. Data. Ser., Nat. Bur. Stand. (U.S.), 61, Part III, 19 pp. (June 1979).

Janz, G. J., and Tomkins, R. P. T., Physical Properties DataCompilations Relevant to Energy Storage. IV. Molten Salts: Data on Additional Single and Multi-Component Salt Systems, Nat. Stand. Ref. Data Ser., Nat. Bur. Stand. (U.S.), 61, Part IV, 870 pp. (July 1981).

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Physical Properties Data Compilations Relevant to Energy Storage.

V. Mechanical Properties Data on Alloys for Use in Flywheels

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This report deals with the physical and mechanical properties of 21 commercial alloys that are candidates for flywheel rotors used as inertial-energy-storage systems. Base metals include aluminum, iron, and titanium. Alloys vary in complexity from simple carbon steels to superalloys. Properties include: mass density, Young's modulus, shear modulus, bulk modulus, Poisson's ratio, yield strength, ultimate strength, fatigue strength, fracture toughness, and creep strength. Property values were collected from many types of sources and were analyzed statistically to detect possible outlying values. For each alloy, the report contains typical chemical composition, typical heat treatment, metallurgical descriptions, and typical property values. The report also shows the variations of these properties and the relative abundances of experimental property values.

Key words: alloy; aluminum alloy; elastic constants; flywheel; iron alloy; mass density; mechanical property; titanium alloy.

1. Introduction

Materials considered here are candidate alloys for flywheel rotors used as inertial-energy-storage systems. The purpose of this study was to determine values of particular physical and mechanical properties of alloys. This was done by compiling data from the engineering-science literature, analyzing the data statistically, discarding "poor" values, and in most cases identifying the trimmed arithmetic mean as the "best" value. In all, 21 commercial alloys were examined:

(1) aluminum alloy 6061-T6
(2) aluminum alloy 7075-T6
(3) titanium-6aluminum-4vanadium
(4) alloy steel 4340
(5) maraging steel 18Ni-300
(6) precipitation-hardened stainless steel 15-7
(7) aluminum alloy 2024
(8) carbon steel 1020
(9) carbon steel 1040
(10) precipitation-hardenable stainless steel AM 355
(11) hardenable stainless steel 440C
(12) wrought stainless steel custom 455
(13) tool steel H-11
(14) titanium-6aluminum-6vanadium
(15) titanium-8molybdenum-8vanadium
(16) resulfurized carbon steel C1141
(17) austenitic Cr-Ni stainless steel 316
(18) iron-based superalloy A286
(19) maraging steel 18Ni-400
(20) iron-based superalloy V57
(21) unitemp 212.

These alloys are described metallurgically in section 2 of this report. Table 1 gives their brief descriptions, chemical compositions, and usual heat treatments.

2. Metallurgical Descriptions of Alloys

Aluminum alloy 6061-T6. This alloy has intermediate strength but excellent corrosion resistance and high plane-strain fracture toughness. It is readily welded by either the GTA or GMA process and with 4043 filler reheat treated welds has approximately the same tensile strength as the parent metal. Fusion welds have excellent corrosion resistance. Resistance welding is difficult and requires special care. Typical applications of 6061 are heavy-duty structures requiring high resistance to corrosion such as truck bodies, marine structures, railroad tank cars, and pipelines. The alloy is available

Table 1. Description of alloys, chemical compositions, and heat treatments.

UNS Number[a]	Description	Chemical Composition	Usual Heat Treatment
A96061	Wrought aluminum alloy, heat treatable	Al bal, Cr 0.04-0.35, Cu 0.15-0.40, Fe 0.7 max, Ag 0.8-1.2, Mn 0.15 max, Si 0.40-0.8, Ti 0.15 max, Zn 0.25 max, Others each 0.05 max, total 0.15 max	Solution treat at 529°C (985°F) and artificially age at 160°C (320°F) for 18h (T6 plate)
A97075	Wrought aluminum alloy, heat treatable	Al bal, Cr 0.18-0.35, Cu 1.2-2.0, Fe 0.50 max, Mg 2.1-2.9, Mn 0.30 max, Si 0.40 max, Ti 0.20 max, Zn 5.1-6.1, Others each 0.05 max, total 0.15 max	Solution heat treat at 482°C (900°F) and artificially age at 121°C (250°F) for 24h (T6 plate)
	Wrought titanium alloy, heat treatable	Al 5.5-6.75, C 0.10 max, Fe 0.40 max, H 0.015 max, N 0.07 max, O 0.30 max, V 3.5-4.5	Solution treat at 816-941°C (1500-1750°F) 15-30 min, water quench, artificially age at 482-538°C (900-1000°F) for 4-8 h, air cool
G43400	Alloy steel	C 0.38-0.43, Cr 0.70-0.90 Mn 0.60-0.80, Mo 0.20-0.30, Ml 1.65-2.00, P 0.035 max, Si 0.20-0.35, S 0.040 max	Austenitized at 829-899°C (1525-1650°F), oil quench, temper at 399-632°C (750-1170°F)
	18Ni 300 maraging steel	Al 0.10, B 0.003, Ca 0.05, C 0.03 max, Co 9.0, Mn 0.10 Mo 4.80, Ni 18.50, P 0.01 max, Si 0.10 max, S 0.01 max, Ti 0.60, Zr 0.02	Solution anneal at 816°C (1500°F) for 1h/in, air cool, age at 482°C (900°F) for 3h
S15700	Precipitation hardenable Cr-Ni-Mo-Al stainless steel	Al 0.75-1.50, C 0.09 max, Cr 14.00-16.00, Mn 1.00 max, Mo 2.00-3.00, Ni 6.50-7.75, P 0.04 max, Si 1.00 max, S 0.03 max	Austenitize at 760-954°C (1700-1750°F), cool rapidly
A92024	Wrought aluminum alloy, heat treatable	Al bal, Cr 0.10 max, Cu 3.8-4.9, Fe 0.50 max, Mg 1.2-1.8, Mn 0.30-0.9, Si 0.50 max, Zn 0.25 max, Other each 0.05 max, total 0.15 max	Solution treat at 493°C (920°F) and artificially age at 191°C (375°F) for 8-16 h depending on product; cold deformation after solution treatment depending on product
G10200	Carbon steel	C 0.18-0.23, Mn 0.30-0.60, P 0.040 max, S 0.050 max, Other sheets and plates, C 0.17-0.23	Hot rolled: 899°C (1650°F) for 1 h, air cool; annealed: 899°C (1650°F) for 1 h, furnace cool; quenched and tempered: 899°C (1650°F), water quench, temper at 204°C (400°F) to 427°C (800°F) for 1 h, air cool
G10400	Carbon steel	C 0.37-0.44, Mn 0.60-0.90, P 0.040 max, S 0.050 max, Other sheets, C 0.36-0.44	Hot rolled: 843°C (1550°F) for 1 h, air cool; annealed: 843°C (1550°F) for 1 h, furnace cool
535500	Cr-Ni-Mo stainless steel, precipitation hardenable (AM 355)	C 0.10-0.15, Cr 15.00-16.00, Mn 0.50-1.25, Mo 2.50-3.25, N 0.07-0.13, Ni 4.00-5.00, P 0.040 max, S 0.030 max, Si 0.50 max	Double aged: solution anneal, age at 732°C (1350°F) 1-2 h, air cool, age at 454°C (850°F) 1-2 h
544004	Stainless steel, hardenable (440 C)	C 0.95-1.20, Cr 16.00-18.00, Mn 1.00 max, Mo 0.75 max, P 0.040 max, S 0.030 max, Si 1.00 max	Solution anneal at 917°C (1700°F) 1 h, oil quench, temper 2 h at 316°C (600°F), 538°C (1000°F) or 760°C (1400°F), and air cool
545500	Stainless steel, wrought precipitation hardenable (custom 455)	C 0.05 max, Cb 0.10-0.50, Cr 11.00-12.50, Cu 1.50-2.50, Mn 0.50 max, Mo 0.50 max, Ni 7.50-9.50, P 0.040 max, S 0.030 max, Si 0.50 max, Ti 0.80-1.40	Solution treat at 816°C (1500°F for 30 min, age at 482°C (900°F 510°C (950°F), 538°C (1000°F), or 566°C (1050°F) for 4 h, air cool
T20811	Tool steel, hot-work (H-11)	C 0.33-0.43, Cr 4.75-5.50, Mn 0.20-0.50, Mo 1.10-1.60, P 0.030 max, S 0.030 max, Si 0.80-1.20, V 0.30-0.60	Solution treat at 1010°C (1850°F), for 1 h, temper twice at 510°C (950°F), 538°C (1000°F), 593°C (1100°F), 621°C (1150°F), or 704°C (1300°F) for 1 to 2 h each, air cool

Table 1. - Continued

UNS NUMBER [a]	Description	Chemical Composition	Usual Heat Treatment
	Wrought titanium alloy, heat treatable (Ti-6Al-6V)	Al 5.0-6.0, C 0.05 max, Cu 0.35-1.0, Fe 0.35-1.0, H 0.015 max, N 0.04 max, O 0.2 max, Sn 1.5-2.5, Ti bal. V 5.0-6.0	(1) Solution treat at 816 to 949°C (1500 to 1740°F) 1/2 - 4h, water quench or air cool, age at 482 to 871°C (900 to 1600°F) 1 - 8 h, air cool (2) Anneal at 704 to 982°C (1300 to 1800°F) 1 - 8 h, air or furnace cool.
	Wrought titanium alloy, heat treatable (Ti-8Mo-8V)	Al 2.5-3.5, C 0.05 max, Fe 1.75-2.25, H 0.015 max, Mo 7.5-8.5, O 0.10-0.18, V 7.5-8.5	(1) Solution treat at 774 to 816°C (1425 to 1500°F) 1/6 - 1 h, air cool or water quench, at 427 to 649°C (800 to 1200°F) 1 - 24 h, air cool (2) Cold roll 9 to 50% (usually 25%), solution treat at 760 to 816°C (1400 to 1500°F) for 1/6 - 1/4 h, air cool, age at 427 to 649°C (800 to 1200°F) 8 - 24 h, air cool
G11410	Resulfurized carbon steel (C1141)	C 0.37-0.45, Mn 1.35-1.65, P 0.040 max, S 0.08-0.13	Heat to 816 to 843°C (1500 to 1550°F), oil quench, temper at 204 to 704°C (400 to 1300°F)
S31600	Austenitic Cr-Ni stainless steel	C 0.08 max, Cr 16.0-18.0, Mn 2.0 max, Mo 2.0-3.0, Ni 10.0-14.0 max, P 0.045 max, S 0.030 max, Si 1-0 max	Anneal at 1038 to 1177°C (1900 to 2150°F), Cool rapidly
K66286	Iron-base superalloy (A286)	Al 0.35 max, 8 0.001-0.01, C 0.08 max, Cr 13.5-16.0, Mn 2.0 max, Mo 1.0-1.5, Ni 24.0-27.0, P 0.04 max, S 0.03 max, Ti 1.9-2.35, V 0.1-0.5	Solution treat at 899 to 982°C (1650 to 1800°F) 1/2 -1 h, oil quench, age at 704 to 760°C (1300 to 1400°F) 16 h, air cool
	18Ni-400 maraging steel [b]	Al 0.12, B 0.003, Ca 0.05, C 0.01, Co 11.50, Fe bal. MO 4.69, Ni 18.0 Mn 0.01, P 0.004, S 0.005, Si 0.003, Ti 1.33, Zr 0.008	(1) Solution treat at 760 to 816°C (1400 to 1500°F) 1/4 - 1 h, air cool, age at 510°C (950°F) 3 - 10 h, air cool (2) Cold deform 25-60%, solution treat at 760 to 816°C (1400 to 1500°F), 1/4 - 1 h, air cool, age at 454 to 593 °C (850-1100°F) 3 - 8 h (3) Solution treat 816°C (1500°F) 1 h, air cool, age at 454 to 482°C (850 to 900°F) 3 h, air cool
	Iron-base superalloy (V57)	Al 0.25, B 0.008, C 0.06, Cr 15.0, Fe bal. Mn 0.25 Mo 1.25, Ni 25.50, Si 0.55, Ti 3.0, V 0.25	Solution treat at 982°C (1800°F) 2 - 4 h, oil quench, age at 732°C (1350°F) 16 h, air cool
	Iron-base superalloy (unitemp 212)	B 0.01, C 0.05-0.15, Cb 0.6, Cr 15.0-17.0, Ni 23.0-27.0, Si 0.15, Ti 4.0, Zr 0.07, Al 0.15	Solution treat at 1010°C (1850°F) 2 h, water quench, double age at 774°C (1425°F) 2 h, air cool, 677°C (1250°F) 16 h, air cool

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[a] Unified Numbering System for Metals and Alloys (Society of Automotive Engineers, Warrendale, Penn., Second Ed., 1977).

[b] Properties quoted are actually for 350-grade.

in all commercial forms and in various sizes. Sheet and plate are available clad with 7072.

Aluminum alloy 7075-T6. This heat-treatable aluminum alloy contains zinc, magnesium, and copper for hardness and has very high strength under static conditions in the T6 temper. It is available in a large range of forms and sizes. In the annealed-and-solution-treated condition it has good formability at ambient temperatures, and in the T6 condition it has good formability at elevated temperatures. The T6 temper has low fracture toughness at room and cryogenic temperatures. A recently introduced T73 temper has a lower tensile and yield strength but improved fracture toughness combined with better stress-corrosion resistance. The unusually high static strength at ambient temperature is not reflected, however, in corresponding high fatigue resistance. Fatigue strengths are comparable to those of 2024 and 2014, which have lower static strength. The loss of fatigue strength is thought to be due to the progressive breakdown of the hardening particles, which lie in the slip regions, progressively reducing their size until they become unstable and dissolve into the matrix, thus losing their hardening function. At high temperatures the alloy loses its strength advantage over 2024 even under static conditions.

Titanium-6aluminum-4vanadium. This alloy is the most widely used of all the alpha-beta titanium compositions. It may be heat treated to a range of strength levels. In its fully aged conditions it is successfully used in highly stressed welded structures. However, in the maximum strength conditions careful attention must be given to the fracture toughness in design of highly stressed parts. Hardenability is limited and sections exceeding 2.5 cm (1 in) may not develop full properties. The alloy has good strength and high stability up to 672 K (750 °F). Very high strength is obtained at cryogenic temperatures. However, the fracture toughness below 116 K (–250 °F) is extremely poor for the fully heat-treated conditions and in the annealed condition inferior to that of 5Al-2.5Sn. Low-temperature applications should use the extra-low-interstitial grades. Welding techniques for sheet have been highly developed and procedures for heavy plate are under development. Forming requires special methods and elevated temperatures.

Alloy steel 4340. 4340, including its variety 4337, which has a slightly lower carbon content, is the preferred common low-alloy steel for air weapons where good strength, high hardenability, and uniformity are desired. It can be heat treated to strength values within a wide range. For low-strength to intermediate-strength applications, other low-alloy steels that have sufficient hardenability possess nearly the same mechanical and other properties as 4340. For high-strength applications, this steel has been found to be superior to other common low-alloy steels and also to some of the recently developed more complex low-alloy steels. 4340 is available in all wrought forms, and castings in this steel are under development. It possesses a fair formability when properly annealed and can be welded by various methods. Forgings in this alloy, heat treated to high strengths, require special measures in design and fabricating.

Maraging steel 18Ni-300. This steel is one of a class of maraging types that develops yield strengths up to 2400 MPa (350 ksi) primarily as a result of complex precipitation reactions in a very low-carbon Fe-Ni martensite. The maraging steels were designed to have superior resistance to crack propagation at high strength levels. In the 18Ni maraging steels, transformation from austenite to martensite occurs above room temperature. Three composition ranges have been specified corresponding to typical yield-strength grades of 1400, 1700, and 1900 MPa (200, 250, and 280 ksi); the latter grade, considered here, being more frequently designated as 2000 MPa (300 ksi). The various yield-strength grades differ principally in the amounts of titanium, molybdenum, and cobalt in the composition. (Material with yield strength up to 2400 MPa (350 ksi) may be obtained from some producers through further adjustments in composition.) The actual strength and toughness will vary considerably within the composition limits and can also depend strongly on the processing history. High fracture toughness, compared with other types of quenched-and-tempered steels, characterizes a properly processed sheet product. The toughness and impact properties of heavy sections are superior to those of conventional medium-carbon, low-alloy, ultrahigh-strength steels heat treated to tensile strength levels exceeding 1700 MPa (250 ksi). However, the fracture properties of heavy sections can be directional and are lowest in the short-transverse direction. This directionability is influenced by the melting and processing conditions.

Corrosion and oxidation resistance are somewhat better than 4340 steel. Resistance to environment-assisted crack propagation is better than 4340 steel at an equivalent level of tensile strength. Hydrogen embrittles the maraging steels, but they exhibit a greater tolerance for hydrogen than conventional low-alloy steels. Formability is excellent in the annealed condition. The steel is readily machined in the annealed condition and can be machined in the fully aged condition. A high degree of dimensional stability is maintained throughout heat treatment. Welding requires special precautions, and the toughness of the weld deposit is generally below that of the parent metal.

Precipitation-hardened stainless steel 15-7. This alloy is a semi-austenite precipitation-hardening stainless steel. It is a modified 17-7PH alloy in which 2 to 3 percent molybdenum is substituted for an equivalent percentage of chromium. Thus, higher strengths can be obtained both at room and elevated temperatures in the various heat treated conditions. The alloy can be considered for use at temperatures up to 811 K (1000 °F). PH 15-7Mo is essentially austenitic at room temperature in either the annealed or solution-treated condition, but can be transformed to martensite by a series of thermal treatments or by cold working. The alloy can then be hardened further by thermal treatment to strengths exceeding 1400 MPa (200 ksi) at room temperature. The alloy is available in sheet, strip, plate, bar, and wire. It can be formed readily in the annealed condition and is welded easily by various methods. Its heat treatment is identical with that of 17-7PH, and much of the information available for the latter alloy applies also to PH 15-7Mo.

Aluminum alloy 2024. This heat-treatable wrought aluminum alloy is the final development of the dural type, which contains copper, magnesium, and manganese as hardeners. Its strength properties in various tempers are among the highest obtainable in aluminum alloys. Including clad 2024, it is still the most used high-strength alloy and it is available in all wrought forms, except forgings. The room-temperature aged conditions of this alloy should not be used where the temperature exceeds 339 K (150 °F) and corrosive conditions exist. The more recently developed artificially aged conditions maintain their strength and corrosion resistance up to a temperature of 422 K (300 °F). The corrosion resistance of the alloy is inferior to that of alloys free from or low in copper. Therefore, where higher corrosion resistance is required, clad 2024 sheet and strip is preferred over the bare material. The alloy is readily formable in either the annealed or solution-treated condition. Limited forming can also be performed in the T4 condition. The machinability of the heat-treated conditions is very good. The alloy may be resistance welded, but fusion welding is not recommended.

Carbon steel 1020. This low-carbon, nonalloyed steel finds extensive use in large-scale construction. It machines easily and forges readily. In general, such a steel combines fair strength with high ductility and excellent fabrication properties such as rolling, drawing, and welding. It is used mainly as hot-rolled, normalized, or annealed.

Carbon steel 1040. This medium-carbon, nonalloyed steel can be quenched and tempered to produce high toughness and good strength properties useful in engineering applications such as shafts, gears, connecting rods, rails, rail axles, and drop-forging dies.

Precipitation-hardenable stainless steel AM355. This alloy is one of a series of age hardenable steels that combine high strength, at temperatures up to 700 K (800 °F) and higher, with the corrosion resistance of stainless steels. In the annealed condition, the alloy is austenitic. Upon forming at room temperature the alloy work hardens very rapidly because of martensite formation during working. Formation of martensite can be avoided by working at temperatures of about 422 K (300 °F) or higher, in which case the alloy forms in much the same manner as conventional austenitic stainless steels. AM355 is a companion alloy to AM350 differing from it by a slightly lower chromium content and a higher carbon. Although designed primarily to meet the demand for heavier sections including plate, bar, and forgings, it is also available in sheet form, which is the principal field for AM350. While the compositions of the two alloys are very similar, the small differences account for significant changes in structure. For example the AM350 has 5 to 20 percent delta ferrite; AM355 usually has little or none.

Hardenable stainless steel 440C. These 17-percent-chromium martensitic stainless steels are produced with various carbon contents. Type 440A contains about 0.70 percent carbon, type 440B about 0.85 percent carbon, and type 440C about 1.10 percent carbon. Type 440F is a free machining grade of type 440C and contains additions of either sulphur or selenium. All these types are used in the hardened condition where a combination of high wear and corrosion resistance is required. Their hardness and wear resistance increase with increasing carbon content, while their shock resistance and ductility decrease.

Wrought stainless steel custom 455. Custom 455 is a versatile, low-carbon, martensitic, age-hardening Cr-Ni stainless steel with good corrosion resistance and favorable fabrication characteristics. It is intended for service up to 700 K (800 °F). A single aging treatment in the range of 755 K (900 °F) to 835 K (1050 °F) develops high tensile and yield strengths. The fracture toughness and ductility in tensile tests decrease with increasing strength level. The K_{ISCC} values in salt solution decrease with lower aging temperatures and are relatively low for the fully-aged condition. It can be readily cold-formed, welded, and machined in the annealed condition. Typical applications include high-strength aircraft fasteners and forgings, components for nuclear reactors, springs, valve stems, gears, shafts, ring seals, retaining rings, pressure vessels, and various parts for use at cryogenic temperatures.

Tool steel H-11. This steel is a modification of the martensitic hot-worked die steel type H-11 with minor changes in chemical composition including slightly higher carbon content. This composition permits heat treating the steel to high strength. It is used extensively in the form of sheet, bar, and forgings at various strengths at room temperature. Also, due to its high chromium content, this steel is of the secondary hardening type and requires tempering temperatures exceeding 755 K (900 °F). Therefore, it is suitable in its full-hardness condition for high strength applications at temperatures up to 811 K (1000 °F) when protected from corrosion and oxidation by appropriate surface treatments. The steel has good formability in the annealed condition, is readily welded and exhibits little distortion when heat treated. This tool steel has relatively good toughness because of low carbon content; it has good to excellent hardness and fair wear resistance and machinability.

Titanium-6aluminum-6vanadium. This is a heat-treatable alpha-beta alloy similar in many respects to Ti-6Al-4V but containing increased content of beta stabilizing elements, which provide higher strength potential at a sacrifice in both toughness and weldability. In forged sections and plate up to 2.5 cm thick, solution-treated-and-aged material has a guaranteed minimum $F_{tu}=1200$ MPa (170 ksi). For forged sections between 8 and 10 cm the corresponding $F_{tu}=1000$ MPa (150 ksi). Response to heat treatment may vary from heat to heat and the correct aging temperature is best determined by tests on the heat in question. As is characteristic of other titanium alloys, exposure to stress at elevated temperature produces changes in the retained mechanical properties. The stress and temperature limits below which these changes will not occur have not yet been established for this alloy. Structural applications should be based on a knowledge of the low toughness characterizing the higher strength conditions of this alloy and the limited toughness of welds. Particular attention should be given to the influence of aggressive environments in the presence of cracks. Such environments include aqueous solutions of chlorides and possibly certain organic solvents such as methanol.

Titanium-8molybdenum-8vanadium. Ti-8Mo-8V-2Fe-3Al is an ageable, metastable beta alloy developed under U.S. Army Contract DA-30-069-ORD-3743. It was developed primarily as a high-strength, formable sheet alloy. But it also possesses hardenability in 10.2 cm (4 in) sections (possibly in 15.2 cm (6 in) sections) and potential as a fastener alloy. In common with its competitor, Ti-13V-11Cr-3Al, the alloy's body-centered-cubic phase (high temperature allotrope) is retained on cooling from solution temperatures to ambient temperature at relatively slow rates. The stability of the beta phase, however, is such that the alloy can be subsequently strengthened by reheating above 700 K (800 °F) through the conventional precipitation of alpha phase (close-packed-hexagonal structure). The alloy is superior in aging kinetics, requiring less aging time to achieve high strength levels. Also, the alloy is claimed to have superior notch fatigue strength, modulus of elasticity, stability at 589 K (600 °F), and, in the annealed condition, salt water corrosion resistance. The major disadvantages of this and other beta alloys compared to alpha-beta alloys are high density and relatively poor creep properties at elevated temperatures. This alloy does not apparently possess smooth fatigue resistance commensurate with its higher strength when compared to Ti-6Al-4V. The alloy is a relatively new composition which, in some respects, is still in a state of development. Thus, reported measurements are tentative.

Resulphurized carbon steel C1141. This alloy steel contains high manganese content. Manganese, a carbide-forming element, increases its hardenability by shifting the nose of the temperature-time-transformation curve to the right. Compared to the medium-carbon-content steel 1040, C1141 has much higher hardenability.

Austenitic Cr-Ni-stainless steel 316. These molybdenum-bearing grades of austenitic stainless steel, which are normally used in the annealed condition, cannot be hardened by heat treatment; however, they can be hardened by cold work. The molybdenum content of 2 to 3 percent in type 316 provides marked improvements in corrosion resistance, particularly pitting corrosion, and in elevated-temperature strength over the non-molybdenum-bearing austenitic stainlesses. The higher molybdenum content of 3 to 4 percent in the less widely used type 317 results in further improvements in these characteristics. They retain usable strength and oxidation resistance at temperatures up to 1089 K (1500 °F). They are, however, susceptible to carbide precipitation and associated intergranular corrosion as a result of exposure to temperatures in the range 755 K (900 °F) to 1144 K (1600 °F). Low carbon modifications, 316L and 317L, are recommended when exposure in this temperature range is unavoidable, although the lower carbon results in lower strength. In cast form, type 316 is generally designated CF3M, CF8M, and CF12M, corresponding to carbon contents of 0.03, 0.08, and 0.12 percent, respectively. The wrought and cast forms are readily weldable, and the wrought forms have good formability in the annealed condition. These alloys are used in various jet-engine parts, exhaust manifolds, heat exchangers, boat trim, chemical-processing equipment, photographic equipment, furnace parts, and orthopedic implants.

Iron-based superalloy A286. This alloy is one of the first and most popular age-hardenable, austenitic, nickel-chromium steels and has pioneered the successful application of this type of superalloy for high-temperature use. It is similar to and a development of the German alloy Tinidur. It is used primarily at temperatures up to 978 K (1300 °F). The alloy is available in sheet, plate, bar, tubing, wire, extrusions, and forgings. Investment castings are also produced. It can be formed and welded.

Maraging steel 18Ni-400. This alloy is consumable vacuum melted and relates strongly metallurgically to the 300-series alloy. Containing less than 0.03 C, it combines a yield strength of about 2800 MPa (400 ksi) with exceptional ductility and toughness for that strength level. An annealing treatment places it in the best condition for machining and forming. Subsequent aging increases hardness by a precipitation reaction in the martensite matrix, with corresponding higher strength properties. Designers and users of this alloy find among the many desirable characteristics: very high yield strengths, good ductility and toughness; high notch-to-smooth tensile strength ratios for a material with this strength capability; good formability characteristics, both hot and cold, with low work-hardening tendencies; easy weldability; freedom from decarburization without use of a protective atmosphere; ease of heat treatment; minimum distortion during heat treatment; excellent hardenability; and a low coefficient of expansion.

Iron-based superalloy V-57. This austenitic stainless-steel alloy has a good combination of tensile and creep rupture properties up to 1089 K (1500 °F) at high stresses. It is a higher titanium and boron modification of A286 stainless steel and is primarily used for some parts of aircraft gas turbines.

Unitemp 212. Because of high chromium content, this alloy is a stainless steel. But it is considered a superalloy because of its superior high-temperature properties. Designed for service to 1033 K (1400 °F), it resists heat and corrosion. At room temperature and above, it has a high strength-to-weight ratio. Its high titanium content causes segregation, which leads to problems in hot working. Its hot-working temperature is relatively low: working above 1339 K (1950 °F) causes cracking. For room-temperature use only, this alloy does not offer the best combination of usual mechanical properties. It has been used for aircraft bolts and for guided-missile components. This alloy was developed and patented by a U.S. steel company as a promising high-strength superalloy. But lack of demand has removed it from production.

3. Properties of Interest

The following properties were covered in this study:

Physical Properties
- (1) mass density.

Elastic Properties
- (2) Young's modulus
- (3) shear modulus
- (4) bulk modulus
- (5) Poisson's ratio.

Mechanical Properties
- (6) yield strength
- (7) ultimate strength
- (8) fatigue strength
- (9) fracture toughness
- (10) creep strength.

Elastic constants are, of course, physical properties. But in this report it is useful to consider them as a separate subclass.

Definitions of the various properties together with their usual SI units are as follows:

g/cm^3	Mass density: mass per unit volume.
GPa	Young's modulus: ratio of uniaxial stress to strain along the stress axis, in either tension or compression.
GPa	Shear modulus: ratio of stress to corresponding strain when stress is either pure shear or pure torsion.
GPa	Bulk modulus: negative ratio of hydrostatic stress (pressure) to volume change.
dimensionless	Poisson's ratio: negative ratio of transverse strain to axial strain in a uniaxially stressed body.
MPa	Yield strength: stress at which a material deviates significantly from linear stress-strain behavior; physically, the onset of plastic deformation.
MPa	Tensile strength: maximum tensile stress a material can sustain, based on original cross-section.

MPa	Fatigue strength: maximum stress a material can sustain for a specified number of load cycles, *N*.
MPa·m$^{1/2}$	Fracture toughness: resistance of a material to fracture in the presence of a sharp crack, under plane-strain, expressed as critical linear-elastic stress-intensity factor, K_{Ic}.
MPa	Creep strength: stress that causes a given creep strain in a given time.

4. Data Collection

Property data were compiled from the following types of sources:

1. handbooks
2. books
3. reports
4. review papers
5. manufacturers' literature
6. engineering-science literature
7. unpublished NBS studies.

Many data were obtained from type-1 sources and from readily available sources. A chronological bibliography of these is given in appendix 1. Type-6 sources were sought only in cases where very limited data were available elsewhere. These type-6 sources were located using:

1. NBS Cryogenic Data Center literature searches
2. Metals Review
3. Metallurgical Abstracts.

From each source, data were recorded on a worksheet (app. 2), which included chemical composition, thermal-mechanical treatment, and other relevant observations.

5. Data Analysis

Two hundred fifty-two data sets (21 materials, 12 properties) were examined statistically for normal distribution when the data set contained at least 5 entries. Data-set size ranged from 0 to 111. Examples of normal-distribution probability plots are shown in figures 1-2. When data were distributed nearly normally, computations were made for: the mean value, the median value, the standard deviation, and a trimmed mean. Trimming consisted of discarding 7 percent of the highest values and 7 percent of the lowest values. Retaining 86 percent of the values amounts to retaining all values within ±1.5σ, where σ is the standard deviation. For a large sample size this corresponds approximately to retaining values within a 90-percent confidence interval. This ±1.5σ cutoff is a judgment based on the experience of our laboratory in previous experimental and analytical studies. In a few cases, data

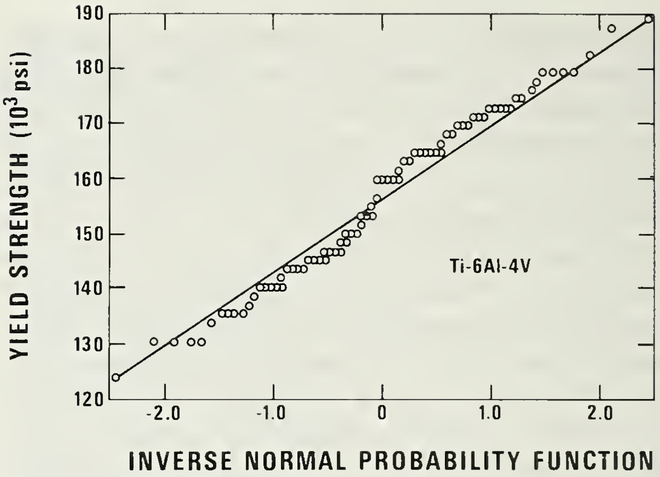

FIGURE 1. Normal-distribution test for yield-strength data for Ti-6Al-4V. The straight line represents normally distributed data. For the materials and properties considered in this study, these data represent an excellent fit to a normal distribution.

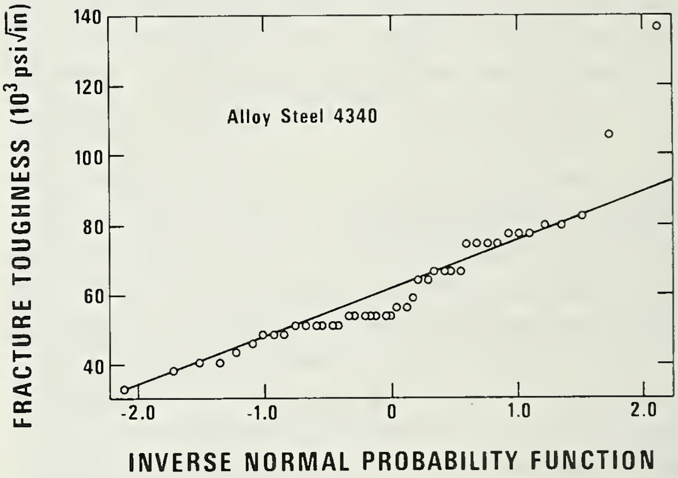

FIGURE 2. Normal-distribution test for fracture-toughness data for alloy steel 4340. Normally distributed data would fall along a straight line. Excluding the two highest values, these data deviate slightly from a normal distribution.

were distributed non-normally and other methods were used to ascertain a "best" value. Strong evidence of non-normal behavior in a probability plot was the exception. Many of these exceptions were for cases where one value was repeated in several references. Such data are best summarized by giving the most prevalent value. Outliers seldom occurred, thus eliminating the need for the trimmed mean in many cases.

6. Results

About 1700 worksheets resulted from the compilation. These worksheets contain 3900 individual data, an average of nearly 200 per alloy, ranging from 14 to 574 per alloy. For brevity, these worksheets are omitted here and the results are summarized by alloy in tables 2-22 in both SI and English units.

7. Discussion

This study suffers from several limitations: reliance principally on secondary sources, neglect of test-variable effects, and use of normal-distribution statistics. Perhaps future related studies will alleviate these limitations.

Despite these drawbacks, this study provides many new insights together with information that may promote further understanding. For the first time, for 21 technological alloys, physical-property and mechanical-property results have been collected from a variety of secondary sources. We see clearly the range of results, the mean value, and the deviation of the mean. The computed standard deviations represent perhaps the most pessimistic statement of uncertainty because the data contain nearly every imaginable uncertainty source: chemical composition, thermomechanical processing, sampling method, test method, experimental error, transcription error, and so on. Where data sets are sufficiently large, we see that practical bounds can be established for the property value. Knowing such bounds is enormously useful and is an essential first step toward determining improved bounds.

That the data may be distributed non-normally seems irrelevant to present purposes. The "errors" may still be random. And, calculating mean values and standard deviations is always valuable for comparing distributions of data, whatever their actual distribution. We chose to exclude extrema from our summary tables because we believe that (in most cases) these represent poor experiments rather than unusual materials.

The veracity of this study can be established partly by comparing its results with the few existing exhaustive studies of property variability. For stainless-steel 316, this is possible because the elastic-property variability was reported recently by Ledbetter (Metal Sci., Dec. 1980, 595-596) and the mechanical-property variability by Sikka (ORNL Report 5384, 1978). Results from neither of these two reports were included in the present study. However, table 23 contains the comparison, which is good for all properties except yield strength, the property with highest uncertainty.

From the data in the tables the average mass-density uncertainty is 0.3 percent, the average elastic-constant uncertainty is 3 percent, and the average mechanical-property uncertainty is 19 percent. Mass density is reported infrequently, but it is well known because of the relative simplicity of measurements and the insensitivity to metallurgical variables such as composition and heat treatment.

None of the four elastic constants—Young's modulus, shear modulus, bulk modulus, Poisson's ratio—is systematically better known than the others. Young's modulus is reported more often than the other three constants combined. Direct bulk-modulus measurements are reported seldomly because such measurements are difficult.

Among the four mechanical properties—yield strength, ultimate strength, fatigue strength, and fracture toughness—the yield and ultimate strength have the lowest uncertainties. Fracture toughness is about 25 percent uncertain; this reflects both experimental inaccuracy and material variability. Fatigue-strength data are relatively scarce because of the long testing times involved; the large uncertainty in these data, about 25 percent, is due mainly to material variability.

8. Acknowledgment

R. P. Mikesell was responsible for data collection, M. W. Austin and G. Maerz for data collation, and J. F. LaBrecque for statistical analysis. J. Dahnke assisted in preparing the report.

TABLE 2(SI). SUMMARY OF PROPERTY DATA FOR ALUMINUM ALLOY 6061-T6

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa) 10^4 Cycles	Fatigue Strength (MPa) 10^5 Cycles	Fatigue Strength (MPa) 10^6 Cycles	Fatigue Strength (MPa) 10^7 Cycles	Fracture Toughness $(MPa \sqrt{m})$
No. Observations	9	17	7	1	4	57	47	11	16	16	14	12
Mean Value	2.71	69.6	26.3	72.4	0.331	275	312	303	223	178	151	28
Median Value	2.71	68.9	26.2	-	0.330	276	310	310	214	166	145	29
Trimmed Mean	2.71	69.6	26.3	-	0.331	274	311	303	230	175	151	
Standard Deviation	0.006	1.9	0.3	-	0.005	20	46	43	45	[illegible]	39	3
Percent Uncertainty	0.2	2.7	1.0	-	1.5	7.3	14.9	14.1	19.5	20.5	25.6	10.5

TABLE 3(SI). SUMMARY OF PROPERTY DATA FOR ALUMINUM ALLOY 7075-T6

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa) 10^4 Cycles	Fatigue Strength (MPa) 10^5 Cycles	Fatigue Strength (MPa) 10^6 Cycles	Fatigue Strength (MPa) 10^7 Cycles	Fracture Toughness $(MPa \sqrt{m})$
No. Observations	8	15	6	1	4	111	42	6	16	12	9	75
Mean Value	2.79	71.8	26.8	70.7	.330	465	529	409	270	199	173	27
Median Value	2.80	71.7	26.9	-	.330	462	531	452	283	214	172	28
Trimmed Mean	2.79	71.8	26.8	-	.330	468	530	409	270	199	173	27
Standard Deviation	0.03	0.9	0.2	-	0.0	53	47	86	51	50	39	6
Percent Uncertainty	0.1	1.2	0.6	-	0.0	11.4	8.9	21.1	18.9	25.3	22.7	21.1

TABLE 4(SI). SUMMARY OF PROPERTY DATA FOR TITANIUM ALLOY Ti-6Al-4V

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)				Fracture Toughness (MPa $\sqrt{m}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	7	15	6	2	6	108	98	5	6	5	2	27
Mean Value	4.43	110.0	42.3	1.05	0.316	994	1143	969	625	508	456	65
Median Value	4.43	110.3	42.4	1.05	0.315	1000	1103	1034	607	490	456	60
Trimmed Mean	4.43	111.0	42.3	1.05	0.316	1000	1085	969	625	508	456	63
Standard Deviation	0.01	3.7	0.5	0.0	0.007	101	103	206	176	160	212	22
Percent Uncertainty	0.25	3.4	1.2	0.0	2.1	1.0	9.5	21.2	28.1	31.7	46.5	35.4

TABLE 5(SI). SUMMARY OF PROPERTY DATA FOR ALLOY STEEL 4340

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)				Fracture Toughness (MPa $\sqrt{m}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	6	14	6	0	2	72	37	5	10	11	7	43
Mean Value	7.85	205	76.5	-	1.93	1494	1733	1168	754	690	613	68
Median Value	7.83	207	75.8	-	1.93	1541	1813	1324	776	724	655	60
Trimmed Mean	7.85	205	76.5	-	1.93	1487	1720	1168	754	690	613	67
Standard Deviation	0.01	6	1.4	-	0.04	240	393	384	25	211	203	21
Percent Uncertainty	0.1	3.0	1.8	-	2.0	16.1	22.8	33.0	32.4	30.6	33.1	30.9

TABLE 6(SI). SUMMARY OF PROPERTY DATA FOR MARAGING STEEL 18Ni-300

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)				Fracture Toughness (MPa $\sqrt{m}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	3	4	1	1	2	84	65	3	4	4	4	38
Mean Value	8.04	190	66.3	167.6	0.318	1925	1982	1356	831	738	707	77
Median Value	8.00	188	-	-	0.318	1940	2034	1310	838	738	703	81
Trimmed Mean	8.04	190	-	-	0.318	1917	1980	1356	831	738	707	78
Standard Deviation	0.14	14	-	-	0.011	230	206	211	199	183	148	17
Percent Uncertainty	1.8	7.5	-	-	3.3	12.0	10.4	15.6	24.0	25.0	20.9	21.8

TABLE 7(SI). SUMMARY OF PROPERTY DATA FOR PRECIPITATION-HARDENED STAINLESS STEEL 15-7

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)				Fracture Toughness (MPa $\sqrt{m}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	3	4	3	0	1	37	36	0	1	1	1	7
Mean Value	7.67	201	77.9	-	0.320	1468	1671	-	1220	1138	1103	63
Median Value	7.67	200	77.9	-	-	1448	1655	-	-	-	-	57
Trimmed Mean	7.67	201	77.9	-	-	1459	1664	-	-	-	-	63
Standard Deviation	0.0	1.7	2.4	-	-	169	157	-	-	-	-	14
Percent Uncertainty	0.0	0.9	3.1	-	-	11.6	9.4	-	-	-	-	21.9

TABLE 8(SI). SUMMARY OF PROPERTY DATA FOR ALUMINUM ALLOY 2024

								Fatigue Strength				
	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	10^4 Cycles	10^5 Cycles (MPa)	10^6 Cycles	10^7 Cycles	Fracture Toughness (MPa $\sqrt{m}$)
No. Observations	6	11	2	0	7	139	50	0	1	2	2	96
Mean Value	2.77	73.1	27.1	-	0.332	417.8	454.4	-	220.6	168.9	131.0	24.4
Median Value	2.77	73.1	27.1	-	0.330	441.3	482.6	-	-	168.9	131.0	24.2
Trimmed Mean	2.77	73.1	27.1	-	0.332	429.6	456.4	-	-	168.9	131.0	24.4
Standard Deviation	0.0	1.4	0.8	-	0.006	75.8	86.2	-	-	53.8	39.3	4.9
Percent Uncertainty	0.0	1.8	2.7	-	1.7	18.1	19.0	-	-	31.7	29.8	20.4

TABLE 9(SI). SUMMARY OF PROPERTY DATA FOR CARBON STEEL 1020

								Fatigue Strength				
	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	10^4 Cycles	10^5 Cycles (MPa)	10^6 Cycles	10^7 Cycles	Fracture Toughness (MPa $\sqrt{m}$)
No. Observations	2	6	1	0	1	45	42	0	0	0	0	2
Mean Value	7.84	206.2	80.0	-	0.288	429.6	619.2	-	-	-	-	95.1
Median Value	7.84	206.2	-	-	-	365.4	544.7	-	-	-	-	95.1
Trimmed Mean	7.84	206.2	-	-	-	439.2	630.9	-	-	-	-	95.1
Standard Deviation	0.0	2.1	-	-	-	195.1	222.7	-	-	-	-	7.0
Percent Uncertainty	0.0	1.1	-	-	-	45.5	36.0	-	-	-	-	7.4

TABLE 10(SI). SUMMARY OF PROPERTY DATA FOR CARBON STEEL 1040

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)				Fracture Toughness (MPa $\sqrt{m}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	0	1	0	0	0	10	12	0	0	0	0	1
Mean Value	-	211.7	-	-	-	458.5	653.6	-	-	-	-	114.3
Median Value	-	-	-	-	-	406.8	634.3	-	-	-	-	-
Trimmed Mean	-	-	-	-	-	458.5	653.6	-	-	-	-	-
Standard Deviation	-	-	-	-	-	188.2	133.1	-	-	-	-	-
Percent Uncertainty	-	-	-	-	-	41.1	20.4	-	-	-	-	-

TABLE 11(SI). SUMMARY OF PROPERTY DATA FOR STAINLESS STEEL AM355

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)				Fracture Toughness (MPa $\sqrt{m}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	4	6	1	0	0	109	104	1	4	4	4	5
Mean Value	7.81	200.6	78.6	-	-	1201	1362	827.4	815.0	703.3	668.2	75.4
Median Value	7.81	200.0	-	-	-	1179	1348	-	817.1	703.3	668.2	81.3
Trimmed Mean	7.81	200.6	-	-	-	1196	1358	-	815.0	703.3	668.2	75.4
Standard Deviation	0.028	5.5	-	-	-	230	219	-	14.5	31.7	55.8	16.2
Percent Uncertainty	0.5	2.6	-	-	-	19.2	16.1	-	1.7	4.5	8.3	21.4

TABLE 12(SI). SUMMARY OF PROPERTY DATA FOR STAINLESS STEEL 440C

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)				Fracture Toughness (MPa $\sqrt{m}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	2	3	1	0	1	11	11	0	0	0	0	0
Mean Value	7.70	203.0	93.1	-	0.284	1220	1448	-	-	-	-	-
Median Value	7.70	200.0	-	-	-	1324	1655	-	-	-	-	-
Trimmed Mean	7.70	203.0	-	-	-	1220	1448	-	-	-	-	-
Standard Deviation	0.0	5.5	-	-	-	578	538	-	-	-	-	-
Percent Uncertainty	0.7	2.7	-	-	-	47.3	37.2	-	-	-	-	-

TABLE 13(SI). SUMMARY OF PROPERTY DATA FOR STAINLESS STEEL CUSTOM 455

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)				Fracture Toughness (MPa $\sqrt{m}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	1	9	1	0	2	51	53	1	2	5	5	4
Mean Value	7.76	197.9	75.8	-	0.300	1489	1572	917	886.0	701.9	685.4	72.3
Median Value	-	196.5	-	-	0.300	1517	1620	-	886.0	717.1	648.1	66.5
Trimmed Mean	-	197.9	-	-	0.300	1480	1564	-	886.0	701.9	685.4	72.3
Standard Deviation	-	4.8	-	-	0.0	255	204	-	44.1	79.3	98.6	29.9
Percent Uncertainty	-	2.6	-	-	0.0	17.1	13.0	-	5.0	11.3	14.4	41.3

TABLE 14(SI). SUMMARY OF PROPERTY DATA FOR TOOL STEEL H-11

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa) 10^4 Cycles	Fatigue Strength (MPa) 10^5 Cycles	Fatigue Strength (MPa) 10^6 Cycles	Fatigue Strength (MPa) 10^7 Cycles	Fracture Toughness (MPa $\sqrt{m}$)
No. Observations	0	7	0	0	0	72	65	5	10	11	7	12
Mean Value	-	205.5	-	-	-	1671	1987	1204	935	788	778	30.1
Median Value	-	207.5	-	-	-	1662	2041	1103	989	883	896	29.1
Trimmed Mean	-	205.5	-	-	-	1704	2013	1204	935	788	778	30.1
Standard Deviation	-	11.7	-	-	-	416	423	196	217	221	243	16.7
Percent Uncertainty	-	5.7	-	-	-	24.9	21.3	16.3	23.2	28.0	31.2	55.4

TABLE 15(SI). SUMMARY OF PROPERTY FOR TITANIUM ALLOY Ti-6Al-6V

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa) 10^4 Cycles	Fatigue Strength (MPa) 10^5 Cycles	Fatigue Strength (MPa) 10^6 Cycles	Fatigue Strength (MPa) 10^7 Cycles	Fracture Toughness (MPa $\sqrt{m}$)
No. Observations	1	16	1	0	1	235	206	11	15	19	20	49
Mean Value	4.539	115.1	44.8	-	0.320	1123.9	1185.9	992.9	820.5	737.7	661.9	310.3
Median Value	-	115.1	-	-	-	1130.7	1199.7	1034.2	855.0	758.4	675.7	268.9
Trimmed Mean	-	114.5	-	-	-	1137.6	1206.6	992.9	848.1	744.6	668.8	303.4
Standard Deviation	-	4.1	-	-	-	137.9	137.9	103.4	110.3	103.4	103.4	103.4
Percent Uncertainty	-	3.3	-	-	-	12	12	11	14	14	16	34

TABLE 16(SI). SUMMARY OF PROPERTY DATA FOR TITANIUM ALLOY Ti-8Mo-8V

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)				Fracture Toughness (MPa $\sqrt{m}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	1	70	0	0	0	159	155	1	1	1	0	10
Mean Value	4.844	106.9	-	-	-	1151.4	1220.4	517.1	551.6	517.1	-	331.0
Median Value	-	106.9	-	-	-	1185.9	1248.0	-	-	-	-	324.1
Trimmed Mean	-	107.6	-	-	-	1144.5	1213.5	-	-	-	-	331.0
Standard Deviation	-	8.3	-	-	-	172.4	179.3	-	-	-	-	55.2
Percent Uncertainty	-	8.0	-	-	-	15	15	-	-	-	-	18

TABLE 17(SI). SUMMARY OF PROPERTY DATA FOR RESULFURIZED CARBON STEEL C1141

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa)				Fracture Toughness (MPa $\sqrt{m}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	2	2	0	0	0	5	4	0	0	0	0	1
Mean Value	7.805	202.0	-	-	-	579.2	792.9	-	-	-	-	427.5
Median Value	7.805	202.0	-	-	-	586.1	827.4	-	-	-	-	-
Trimmed Mean	7.805	202.0	-	-	-	579.2	792.9	-	-	-	-	-
Standard Deviation	0.0	2.8	-	-	-	103.4	131.0	-	-	-	-	-
Percent Uncertainty	0.0	1.2	-	-	-	18	17	-	-	-	-	-

TABLE 18(SI). SUMMARY OF PROPERTY DATA FOR AUSTENITIC Cr-Ni STAINLESS STEEL 316

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa) 10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	Fracture Toughness (MPa $\sqrt{m}$)
No. Observations	7	11	4	1	3	50	56	1	1	1	1	1
Mean Value	7.971	195.1	79.9	177.9	0.294	296.5	627.4	268.9	234.4	213.7	199.9	2364.9
Median Value	7.971	193.1	79.9	-	0.295	284.2	586.1	-	-	-	-	-
Trimmed Mean	7.971	195.1	79.9	-	0.294	268.9	620.5	-	-	-	-	-
Standard Deviation	0.028	9.7	3.4	-	0.004	165.5	131.0		-	-	-	-
Percent Uncertainty	0.3	5.1	4.8	-	1.2	56	21		-	-	-	-

TABLE 19(SI). SUMMARY OF PROPERTY DATA FOR IRON BASED SUPERALLOY A286

	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength (MPa) 10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	Fracture Toughness (MPa $\sqrt{m}$)
No. Observations	7	17	8	1	6	72	86	2	4	4	2	3
Mean Value	7.944	196.5	73.1	154.4	0.301	820.5	999.7	517.1	503.3	393.0	420.6	1013.5
Median Value	7.916	199.9	72.4	-	0.303	730.8	1048.0	517.1	558.5	420.6	420.6	999.7
Trimmed Mean	7.944	195.8	73.1	-	0.301	841.2	992.9	517.1	503.3	393.0	420.6	1013.5
Standard Deviation	0.055	9.0	1.4	-	0.006	255.1	303.4	241.3	137.9	103.4	27.6	234.4
Percent Uncertainty	0.5	4.5	2.2	-	2.1	31	30	47	28	27	6	23

TABLE 20(SI). SUMMARY OF PROPERTY DATA FOR MARAGING STEEL 18Ni-400

	Density	Young's Modulus	Shear Modulus	Bulk Modulus	Poisson's Ratio	Yield Strength	Tensile Strength	Fatigue Strength				Fracture Toughness
	(g/cm^3)	(GPa)	(GPa)	(GPa)		(MPa)	(MPa)	10^4 Cycles	10^5 Cycles (MPa)	10^6 Cycles	10^7 Cycles	(MPa $\sqrt{m}$)
No. Observations	1	2	0	0	6	92	94	2	2	2	1	27
Mean Value	8.082	189.6	-	-	0.300	2275.3	2337.3	1234.2	992.9	820.5	765.3	295.8
Median Value	-	189.6	-	-	0.295	2316.7	2378.7	1234.2	992.9	820.5	-	272.3
Trimmed Mean	-	189.6	-	-	0.300	2268.4	2337.3	1234.2	992.9	820.5	-	297.2
Standard Deviation	-	14.5	-	-	0.045	186.2	165.5	6.9	89.6	27.6	-	89.6
Percent Uncertainty	-	7.7	-	-	15.1	8	7	1	9	3	-	30

TABLE 21(SI). SUMMARY OF PROPERTY DATA FOR IRON BASED SUPERALLOY V57

	Density	Young's Modulus	Shear Modulus	Bulk Modulus	Poisson's Ratio	Yield Strength	Tensile Strength	Fatigue Strength				Fracture Toughness
	(g/cm^3)	(GPa)	(GPa)	(GPa)		(MPa)	(MPa)	10^4 Cycles	10^5 Cycles (MPa)	10^6 Cycles	10^7 Cycles	(MPa $\sqrt{m}$)
No. Observations	3	2	2	0	1	6	6	0	2	4	4	0
Mean Value	7.916	196.5	78.6	-	0.294	868.7	1213.5	-	703.3	524.0	482.6	-
Median Value	7.916	196.5	78.6	-	-	848.1	1199.7	-	703.3	537.8	482.6	-
Trimmed Mean	7.916	196.5	78.6	-	-	861.9	1213.5	-	703.3	524.0	482.6	-
Standard Deviation	0.028	0.7	1.4	-	-	62.1	41.4	-	275.8	75.8	75.8	-
Percent Uncertainty	0.2	0.5	1.9	-	-	7	3	-	40	15	16	-

TABLE 22(SI). SUMMARY OF PROPERTY DATA FOR UNITEMP 212

									Fatigue Strength			
	Density (g/cm^3)	Young's Modulus (GPa)	Shear Modulus (GPa)	Bulk Modulus (GPa)	Poisson's Ratio	Yield Strength (MPa)	Tensile Strength (MPa)	10^4 Cycles	10^5 Cycles (MPa)	10^6 Cycles	10^7 Cycles	Fracture Toughness $(MPa \sqrt{m})$
No. Observations	1	1	0	0	0	2	3	0	0	0	0	0
Mean Value	7.916	200	-	-	-	930.8	1351.4	-	-	-	-	-
Median Value	-	-	-	-	-	930.8	1289.3	-	-	-	-	-
Trimmed Mean	-	-	-	-	-	930.8	1351.4	-	-	-	-	-
Standard Deviation	-	-	-	-	-	6.9	110.3	-	-	-	-	-
Percent Uncertainty	-	-	-	-	-	1	8	-	-	-	-	-

TABLE 2(E). SUMMARY OF PROPERTY DATA FOR ALUMINUM ALLOY 6061-T6

									Fatigue Strength			
	Density (lb/in^3)	Young's Modulus $(10^6$ psi)	Shear Modulus $(10^6$ psi)	Bulk Modulus $(10^6$ psi)	Poisson's Ratio	Yield Strength $(10^3$ psi)	Tensile Strength $(10^3$ psi)	10^4 Cycles	10^5 Cycles $(10^3$ psi)	10^6 Cycles	10^7 Cycles	Fracture Toughness $(10^3$ psi $\sqrt{in})$
No. Observations	9	17	7	1	4	57	47	11	16	16	14	12
Mean Value	0.0979	10.1	3.81	10.5	0.331	40	45	44	34	26	22	26
Median Value	0.0980	10.0	3.80	-	0.330	40	45	45	31	24	21	27
Trimmed Mean	0.0979	10.1	3.81	-	0.331	40	45	44	34	25	22	26
Standard Deviation	0.0002	0.3	0.04	-	0.005	3	7	6	7	5	6	3
Percent Uncertainty	0.2	2.7	1.0	-	1.5	7.3	14.9	14.1	19.5	20.5	25.6	10.5

TABLE 3(E). SUMMARY OF PROPERTY DATA FOR ALUMINUM ALLOY 7075-T6

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength (10^3 psi)				Fracture Toughness (10^3 psi $\sqrt{\text{in}}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	8	15	6	1	4	111	42	6	16	12	9	75
Mean Value	0.1007	10.41	3.89	10.3	0.330	67	77	59	39	29	25	25
Median Value	0.1010	10.40	3.90	-	0.330	67	77	66	41	31	25	25
Trimmed Mean	0.1007	10.42	3.89	-	0.330	68	77	59	39	29	25	25
Standard Deviation	0.0010	0.13	0.02	-	0.0	8	7	13	7	7	6	5
Percent Uncertainty	0.1	1.2	0.6	-	0.0	11.4	8.9	21.1	18.9	25.3	22.7	21.1

TABLE 4(E). SUMMARY OF PROPERTY DATA FOR TITANIUM ALLOY Ti-6Al-4V

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength (10^3 psi)				Fracture Toughness (10^3 psi $\sqrt{\text{in}}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	7	15	6	2	6	108	98	5	6	5	2	27
Mean Value	0.1601	16.0	6.14	0.152	0.316	144	157	141	91	74	66	60
Median Value	0.1600	16.0	6.15	0.152	0.315	145	160	150	88	71	66	54
Trimmed Mean	0.1601	16.1	6.14	0.152	0.316	145	157	141	91	74	66	57
Standard Deviation	0.0004	0.5	0.07	0.0	0.007	15	15	30	26	23	31	20
Percent Uncertainty	0.25	3.4	1.2	0.0	2.1	10.0	9.5	21.2	28.1	31.7	46.5	35.4

TABLE 5(E). SUMMARY OF PROPERTY DATA FOR ALLOY STEEL 4340

									Fatigue Strength			
	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	10^4 Cycles	10^5 Cycles (10^3 psi)	10^6 Cycles	10^7 Cycles	Fracture Toughness (10^3 psi $\sqrt{in}$)
No. Observations	6	14	6	0	2	72	37	5	10	11	7	43
Mean Value	0.283	29.7	11.1	-	0.28	217	251	169	109	100	89	62
Median Value	0.283	30.0	11.0	-	0.28	224	263	192	113	105	95	55
Trimmed Mean	0.283	29.7	11.1	-	0.28	216	250	169	109	100	89	61
Standard Deviation	0.0004	0.9	0.2	-	0.06	35	57	56	35	31	29	19
Percent Uncertainty	0.1	3.0	1.8	-	20.4	16.1	22.8	33.0	32.4	30.6	33.1	30.9

TABLE 6(E). SUMMARY OF PROPERTY DATA FOR MARAGING STEEL 18Ni-300

									Fatigue Strength			
	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	10^4 Cycles	10^5 Cycles (10^3 psi)	10^6 Cycles	10^7 Cycles	Fracture Toughness (10^3 psi $\sqrt{in}$)
No. Observations	3	4	1	1	2	84	65	3	4	4	4	38
Mean Value	0.290	27.6	9.6	24.3	0.318	279	288	197	121	107	103	70
Median Value	0.289	27.2	-	-	0.318	282	295	190	122	107	102	74
Trimmed Mean	0.290	27.6	-	-	0.318	278	287	197	121	107	103	71
Standard Deviation	0.005	2.1	-	-	0.011	33	30	31	29	27	21	15
Percent Uncertainty	1.7	7.5	-	-	3.3	12.0	10.4	15.6	24.0	25.0	20.9	21.8

TABLE 7(E). SUMMARY OF PROPERTY DATA FOR PRECIPITATION-HARDENED STAINLESS STEEL 15-7

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength (10^3 psi) 10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	Fracture Toughness (10^3 psi $\sqrt{in}$)
No. Observations	3	4	3	0	1	37	36	0	1	1	1	7
Mean Value	0.277	29.1	11.3	-	0.320	213	242	-	177	165	160	57
Median Value	0.277	29.0	11.3	-	-	210	240	-	-	-	-	52
Trimmed Mean	0.277	29.1	11.3	-	-	212	241	-	-	-	-	57
Standard Deviation	0.0	0.3	0.4	-	-	25	23	-	-	-	-	12
Percent Uncertainty	0.0	0.9	3.1	-	-	11.6	9.4	-	-	-	-	21.9

TABLE 8(E). SUMMARY OF PROPERTY DATA FOR ALUMINUM ALLOY 2024

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength (10^3 psi) 10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	Fracture Toughness (10^3 psi $\sqrt{in}$)
No. Observations	6	11	2	0	7	139	50	0	1	2	2	96
Mean Value	0.1000	10.6	3.93	-	0.332	60.6	65.9	-	32	24.5	19.0	22.2
Median Value	0.1000	10.6	3.93	-	0.330	64.0	70.0	-	-	24.5	19.0	22.0
Trimmed Mean	0.1000	10.6	3.93	-	0.332	62.3	66.2	-	-	24.5	19.0	22.2
Standard Deviation	0.0	0.2	0.11	-	0.006	11.0	12.5	-	-	7.8	5.7	4.5
Percent Uncertainty	0.0	1.8	2.7	-	1.7	18.1	19.0	-	-	31.7	29.8	20.4

TABLE 9(E). SUMMARY OF PROPERTY DATA FOR CARBON STEEL 1020

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength (10^3 psi)				Fracture Toughness (10^3 psi $\sqrt{in}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	2	6	1	0	1	45	42	0	0	0	0	2
Mean Value	0.283	29.9	11.6	-	0.288	62.3	89.8	-	-	-	-	86.5
Median Value	0.283	29.9	-	-	-	53.0	79.0	-	-	-	-	86.5
Trimmed Mean	0.283	29.9	-	-	-	63.7	91.5	-	-	-	-	86.5
Standard Deviation	0.0	0.3	-	-	-	28.3	32.3	-	-	-	-	6.4
Percent Uncertainty	0.0	1.1	-	-	-	45.5	36.0	-	-	-	-	7.4

TABLE 10(E). SUMMARY OF PROPERTY DATA FOR CARBON STEEL 1040

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength (10^3 psi)				Fracture Toughness (10^3 psi $\sqrt{in}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	0	1	0	0	0	10	12	0	0	0	0	1
Mean Value	-	30.7	-	-	-	66.5	94.8	-	-	-	-	104.0
Median Value	-	-	-	-	-	59.0	92.0	-	-	-	-	-
Trimmed Mean	-	-	-	-	-	66.5	94.8	-	-	-	-	-
Standard Deviation	-	-	-	-	-	27.3	19.3	-	-	-	-	-
Percent Uncertainty	-	-	-	-	-	41.1	20.4	-	-	-	-	-

TABLE 11(E). SUMMARY OF PROPERTY DATA FOR STAINLESS STEEL AM355

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength				Fracture Toughness (10^3 psi $\sqrt{in}$)
								10^4 Cycles	10^5 Cycles (10^3 psi)	10^6 Cycles	10^7 Cycles	
No. Observations	4	6	1	0	0	109	104	1	4	4	4	5
Mean Value	0.282	29.1	11.4	-	-	174.2	197.5	120.0	118.2	102.0	97.0	68.6
Median Value	0.282	29.0	-	-	-	171.0	195.5	-	118.5	102.0	97.0	74.0
Trimmed Mean	0.282	29.1	-	-	-	173.4	197.0	-	118.2	102.0	97.0	68.6
Standard Deviation	0.001	0.8	-	-	-	33.4	31.7	-	2.1	4.6	8.1	14.7
Percent Uncertainty	0.5	2.6	-	-	-	19.2	16.1	-	1.7	4.5	8.3	21.4

TABLE 12(E). SUMMARY OF PROPERTY DATA FOR STAINLESS STEEL 440C

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength				Fracture Toughness (10^3 psi $\sqrt{in}$)
								10^4 Cycles	10^5 Cycles (10^3 psi)	10^6 Cycles	10^7 Cycles	
No. Observations	2	3	1	0	1	11	11	0	0	0	0	0
Mean Value	0.278	29.5	13.5	-	0.284	177.0	210.0	-	-	-	-	-
Median Value	0.278	29.0	-	-	-	192.0	240.0	-	-	-	-	-
Trimmed Mean	0.278	29.5	-	-	-	177.0	210.0	-	-	-	-	-
Standard Deviation	0.0	0.8	-	-	-	83.8	78.1	-	-	-	-	-
Percent Uncertainty	0.7	2.7	-	-	-	47.3	37.2	-	-	-	-	-

TABLE 13(E). SUMMARY OF PROPERTY DATA FOR STAINLESS STEEL CUSTOM 455

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength				Fracture Toughness (10^3 psi $\sqrt{in}$)
								10^4 Cycles	10^5 Cycles (10^3 psi)	10^6 Cycles	10^7 Cycles	
No. Observations	1	9	1	0	2	51	53	1	2	5	5	4
Mean Value	0.280	28.7	11.0	-	0.300	216.0	228.0	133.0	128.5	101.8	99.4	65.8
Median Value	-	28.5	-	-	0.300	220.0	235.0	-	128.5	104.0	94.0	60.5
Trimmed Mean	-	28.7	-	-	0.300	214.6	226.9	-	128.5	101.8	99.4	65.8
Standard Deviation	-	0.7	-	-	0.0	37.0	29.6	-	6.4	11.5	14.3	27.2
Percent Uncertainty	-	2.6	-	-	0.0	17.1	13.0	-	5.0	11.3	14.4	41.3

TABLE 14(E). SUMMARY OF PROPERTY DATA FOR TOOL STEEL H-11

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength				Fracture Toughness (10^3 psi $\sqrt{in}$)
								10^4 Cycles	10^5 Cycles (10^3 psi)	10^6 Cycles	10^7 Cycles	
No. Observations	0	7	0	0	0	72	65	5	10	11	7	12
Mean Value	-	29.8	-	-	-	242.4	288.2	174.6	135.6	114.3	112.9	27.4
Median Value	-	30.1	-	-	-	241.0	296.0	160.0	143.5	128.0	130.0	26.5
Trimmed Mean	-	29.8	-	-	-	247.1	291.9	174.6	135.6	114.3	112.9	27.4
Standard Deviation	-	1.7	-	-	-	60.3	61.3	28.4	31.5	32.0	35.3	15.2
Percent Uncertainty		5.7	-	-	-	24.9	21.3	16.3	23.2	28.0	31.2	55.4

TABLE 15(E). SUMMARY OF PROPERTY DATA FOR TITANIUM ALLOY Ti-6Al-6V

	Density	Young's Modulus	Shear Modulus	Bulk Modulus	Poisson's Ratio	Yield Strength	Tensile Strength	Fatigue Strength				Fracture Toughness
	$(\mathrm{lb/in}^3)$	$(10^6$ psi)	$(10^6$ psi)	$(10^6$ psi)		$(10^3$ psi)	$(10^3$ psi)	10^4 Cycles	10^5 Cycles $(10^3$ psi)	10^6 Cycles	10^7 Cycles	$(10^3$ psi $\sqrt{\mathrm{in}})$
No. Observations	1	16	1	0	1	235	206	11	15	19	20	49
Mean Value	0.164	16.7	6.5	-	0.320	163	172	144	119	107	96	45
Median Value	-	16.7	-	-	-	164	174	150	124	110	98	39
Trimmed Mean	-	16.6	-	-	-	165	175	144	123	108	97	44
Standard Deviation	-	0.6	-	-	-	20	20	15	16	15	15	15
Percent Uncertainty	-	3.3	-	-	-	12	12	11	14	14	16	34

TABLE 16(E). SUMMARY OF PROPERTY DATA FOR TITANIUM ALLOY Ti-8Mo-8V

	Density	Young's Modulus	Shear Modulus	Bulk Modulus	Poisson's Ratio	Yield Strength	Tensile Strength	Fatigue Strength				Fracture Toughness
	$(\mathrm{lb/in}^3)$	$(10^6$ psi)	$(10^6$ psi)	$(10^6$ psi)		$(10^3$ psi)	$(10^3$ psi)	10^4 Cycles	10^5 Cycles $(10^3$ psi)	10^6 Cycles	10^7 Cycles	$(10^3$ psi $\sqrt{\mathrm{in}})$
No. Observations	1	70	0	0	0	159	155	1	1	1	0	10
Mean Value	0.175	15.5	-	-	-	167	177	75	80	75	-	48
Median Value	-	15.5	-	-	-	172	181	-	-	-	-	47
Trimmed Mean	-	15.6	-	-	-	166	176	-	-	-	-	48
Standard Deviation	-	1.2	-	-	-	25	26	-	-	-	-	8
Percent Uncertainty	-	8.0	-	-	-	15	15	-	-	-	-	18

TABLE 17(E). SUMMARY OF PROPERTY DATA FOR RESULFURIZED CARBON STEEL C1141

									Fatigue Strength (10^3 psi)			
	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	Fracture Toughness (10^3 psi $\sqrt{in}$)
No. Observations	2	2	0	0	0	5	4	0	0	0	0	1
Mean Value	0.282	29.3	-	-	-	84	115	-	-	-	-	62
Median Value	0.282	29.3	-	-	-	85	120	-	-	-	-	-
Trimmed Mean	0.282	29.3	-	-	-	84	115	-	-	-	-	-
Standard Deviation	0.0	0.4	-	-	-	15	19	-	-	-	-	-
Percent Uncertainty	0.0	1.2	-	-	-	18	17	-	-	-	-	-

TABLE 18(E). SUMMARY OF PROPERTY DATA FOR AUSTENITIC Cr-Ni STAINLESS STEEL 316

									Fatigue Strength (10^3 psi)			
	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	Fracture Toughness (10^3 psi $\sqrt{in}$)
No. Observations	7	11	4	1	3	50	56	1	1	1	1	1
Mean Value	0.288	28.3	11.6	25.8	0.294	43	91	39	34	31	29	343
Median Value	0.288	28.0	11.6	-	0.295	36	85	-	-	-	-	-
Trimmed Mean	0.288	28.3	11.6	-	0.294	39	90	-	-	-	-	-
Standard Deviation	0.001	1.4	0.5	-	0.004	24	19	-	-	-	-	-
Percent Uncertainty	0.3	5.1	4.8	-	1.2	56	21	-	-	-	-	-

TABLE 19(E). SUMMARY OF PROPERTY DATA FOR IRON BASED SUPERALLOY A286

	Density	Young's	Shear	Bulk	Poisson's	Yield	Tensile	Fatigue Strength				Fracture
		Modulus	Modulus	Modulus	Ratio	Strength	Strength	10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	Toughness
	(lb/in^3)	(10^6 psi)	(10^6 psi)	(10^6 psi)		(10^3 psi)	(10^3 psi)		(10^3 psi)			(10^3 psi $\sqrt{in}$)
No. Observations	7	17	8	1	6	72	86	2	4	4	2	3
Mean Value	0.287	28.5	10.6	22.4	0.301	119	145	75	73	57	61	147
Median Value	0.286	29.0	10.5	-	0.303	106	152	75	81	61	61	145
Trimmed Mean	0.287	28.4	10.6	-	0.301	122	144	75	73	57	61	147
Standard Deviation	0.002	1.3	0.2	-	0.006	37	44	35	20	15	4	34
Percent Uncertainty	0.5	4.5	2.2	-	2.1	31	30	47	28	27	6	23

TABLE 20(E). SUMMARY OF PROPERTY DATA FOR MARAGING STEEL 18Ni-400

	Density	Young's	Shear	Bulk	Poisson's	Yield	Tensile	Fatigue Strength				Fracture
		Modulus	Modulus	Modulus	Ratio	Strength	Strength	10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	Toughness
	(lb/in^3)	(10^6 psi)	(10^6 psi)	(10^6 psi)		(10^3 psi)	(10^3 psi)		(10^3 psi)			(10^3 psi $\sqrt{in}$)
No. Observations	1	2	0	0	6	92	94	2	2	2	1	27
Mean Value	0.292	27.5	-	-	0.300	330	339	179	144	119	111	42.9
Median Value	-	27.5	-	-	0.295	336	345	179	144	119	-	39.5
Trimmed Mean	-	27.5	-	-	0.300	329	339	179	144	119	-	43.1
Standard Deviation	-	2.1	-	-	0.045	27	24	1	13	4	-	13.0
Percent Uncertainty	-	7.7	-	-	15.1	8	7	1	9	3	-	30

TABLE 21(E). SUMMARY OF PROPERTY DATA FOR IRON BASED SUPERALLOY V57

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength (10^3 psi)				Fracture Toughness (10^3 psi $\sqrt{in}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	3	2	2	0	1	6	6	0	2	4	4	0
Mean Value	0.286	28.5	11.4	-	0.294	126	176	-	102	76	70	-
Median Value	0.286	28.5	11.4	-	-	123	174	-	102	78	70	-
Trimmed Mean	0.286	28.5	11.4	-	-	125	176	-	102	76	70	-
Standard Deviation	0.001	0.1	0.2	-	-	9	6	-	40	11	11	-
Percent Uncertainty	0.2	0.5	1.9	-	-	7	3	-	40	15	16	-

TABLE 22(E). SUMMARY OF PROPERTY DATA FOR UNITEMP 212

	Density (lb/in^3)	Young's Modulus (10^6 psi)	Shear Modulus (10^6 psi)	Bulk Modulus (10^6 psi)	Poisson's Ratio	Yield Strength (10^3 psi)	Tensile Strength (10^3 psi)	Fatigue Strength (10^3 psi)				Fracture Toughness (10^3 psi $\sqrt{in}$)
								10^4 Cycles	10^5 Cycles	10^6 Cycles	10^7 Cycles	
No. Observations	1	1	0	0	0	2	3	0	0	0	0	0
Mean Value	0.286	29.0	-	-	-	135	196	-	-	-	-	-
Median Value	-	-	-	-	-	135	187	-	-	-	-	-
Trimmed Mean	-	-	-	-	-	135	196	-	-	-	-	-
Standard Deviation	-	-	-	-	-	1	16	-	-	-	-	-
Percent Uncertainty	-	-	-	-	-	1	8	-	-	-	-	-

TABLE 23. FOR STAINLESS STEEL 316, COMPARISON OF PRESENT RESULTS WITH TWO OTHER VARIABILITY STUDIES.

	Here	There	Ratio
Density (g/cm^3)	7.971	7.958	1.002
Young's Modulus (GPa)	195.1	194.6	1.003
Shear Modulus (GPa)	79.9	75.2	1.060
Bulk Modulus (GPa)	177.9	157.5	1.130
Poisson's Ratio	0.294	0.294	1.000
Yield Strength (MPa)	297	227	1.308
Tensile Strength (MPa)	627	583	1.075

Represents a single value.

Appendix 1. Physical and Mechanical Properties of Technological Alloys: A Data-Source Bibliography

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Appendix 2.

Material: ____

Composition (Pct.):	Min.	Avg.	Max.	Element	Wt.	At.
	______	______	______	______	______	______
	______	______	______	______		
	______	______	______	______		
	______	______	______	______		
	______	______	______	______		
	______	______	______	______		
	______	______	______	______		
	______	______	______	______		
	______	______	______	______		
	______	______	______	______		

Thermal–Mechanical Treatment: ______________________________
____
______________________________ Form: ______________

Mass Density	____g/cm^3	____lb/in^3	Comments: ______________
Young's Modulus	____GPa	____10^6 psi	______________________
			______________________
Shear Modulus	____GPa	____10^6 psi	______________________
			______________________
Bulk Modulus	____GPa	____10^6 psi	______________________
Poisson's Ratio	____		______________________
			______________________
Yield Strength	____MPa	____ksi	______________________
			______________________
Ultimate Strength	____MPa	____ksi	______________________
Fatigue Strength	____MPa	____ksi	____cycles
	____	____	____
	____	____	____
	____	____	____

Fracture Toughness	____MPa$\sqrt{m}$	____ksi$\sqrt{in}$		
Creep Strength	____MPa	____ksi	____strain	____hours
	____	____	____	____
	____	____	____	____
	____	____	____	____

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H. M. Ledbetter

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This report deals with the physical and mechanical properties of twenty-one commercial alloys that are candidates for flywheel rotors used as inertial-energy-storage systems. Base metals include aluminum, iron, and titanium. Alloys vary in complexity from simple carbon steels to superalloys. Properties include: mass density, Young's modulus, shear modulus, bulk modulus, Poisson's ratio, yield strength, ultimate strength, fatigue strength, fracture toughness, and creep strength. Property values were collected from many types of sources and were analyzed statistically to detect possible outlying values. For each alloy, the report contains typical chemical composition, typical heat treatment, metallurgical descriptions, and typical property values. The report also shows the variations of these properties and the relative abundances of experimental property values.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Alloy; aluminum alloy; elastic constants; flywheel; iron alloy; mass density; mechanical property; titanium alloy.

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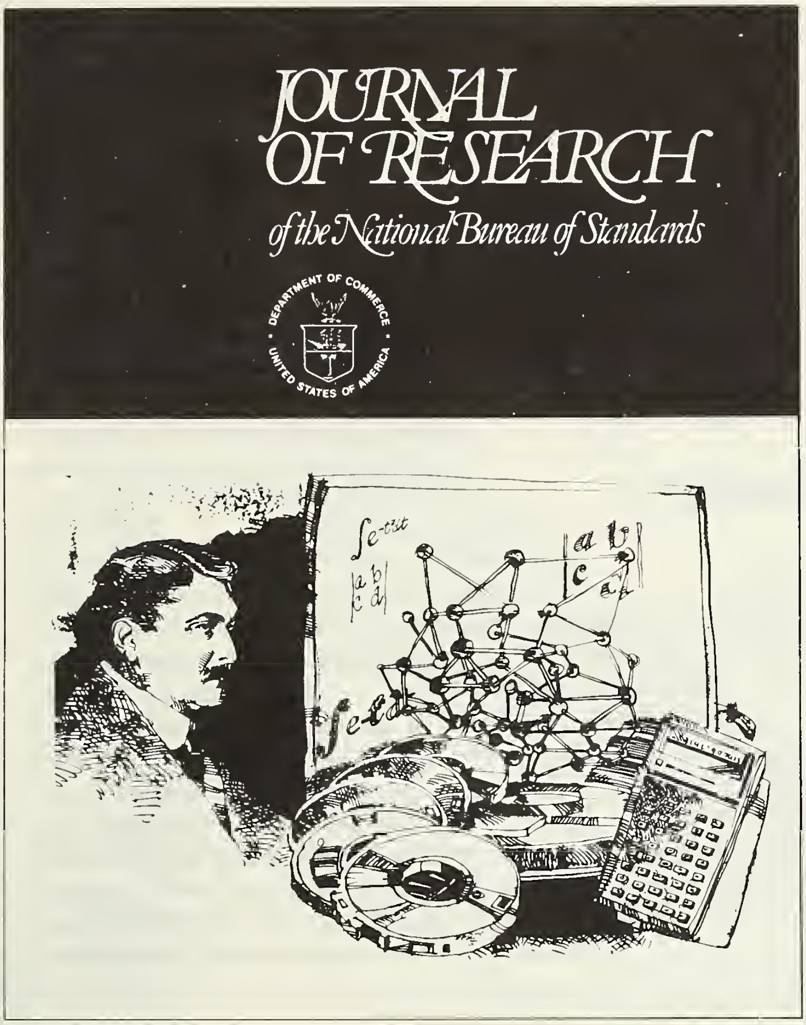
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